From Fringes to the USNO Navy Prototype Optical Interferometer Astrometric Catalog

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ABSTRACT

We report progress on the United States Naval Observatory, Navy Prototype Optical Interferometer, Astrometric Catalog (UNAC). This catalog uses observations from eight astrometric observation runs (Jan. 2005 – Nov. 2009) at the Navy Prototype Optical Interferometer (NPOI). The goal of the first release of the UNAC is to provide an astrometric catalog of at least 100 bright (V < 6) stars with precise positions accurate to < 16 milliarcseconds. In this paper we report on some of the data processing methods used to obtain absolute astrometric positions from optical interferometer data. We also discuss plans for assessing the accuracy of our interferometrically derived absolute astrometric positions.

Keywords: Optical interferometry, astrometry, NPOI

1. INTRODUCTION

The Navy Prototype Optical Interferometer[1] (NPOI), is a six element optical interferometer located on Anderson Mesa, AZ. The interferometer includes arrays that are used for imaging and for astrometry. The astrometric array consists of four 50-cm siderostats that feed 12-cm beams into a vacuum beam relay system. The astrometric array includes baselines ranging from 19 m to 38 m. The astrometric stations have extensive station metrology[2] that includes a nearly end-to-end "constant-term" metrology system[3]. The NPOI has rapid tip-tilt star tracking and uses active group-delay fringe tracking over 16 wavelength channels ranging from ~ 550 – 850 nm.

In this paper we describe progress with the NPOI towards obtaining a high precision astrometric catalog of a small number of bright stars. Since the NPOI, like all interferometers, is a pointed instrument rather than a wide field survey instrument, we have concentrated on obtaining high precision astrometric measurements of slightly more than 100 stars. In November 2009, we completed observations for the first release of the USNO Navy Prototype Optical Interferometer Astrometric Catalog (UNAC). The goal of this catalog is to produce precise, accurate (< 16 milliarcseconds) astrometric positions for ~ 100 bright (V < 6) stars.

2. DATA AND DISCUSSION

The path from fringes to precise and accurate astrometric positions for an optical interferometer is by no means trivial. At the astrometric baselines of the NPOI, one micron of baseline uncertainty corresponds to ~ 15 milliarcseconds (mas) of positional uncertainty on the sky. For comparison, the atmosphere inserts hundreds of microns of random delay into the predictable geometric delays. In addition, the interferometer stations themselves move around by hundreds to a few thousand microns during the course of a night of observations. These two effects conspire to make astrometric measurements much more challenging than a simple geometry problem.

The NPOI is fully outfitted with internal metrology systems that measure the motions of the stations in the interferometer as well as motions in the vacuum feed system that serves to transport the light from the stations to the beam combiner. These data are used during the data reductions to properly account for the internal motions of the stations in the interferometer.

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The effects of the atmosphere are determined by careful analysis of the curvature of the fringe phase across the 16 channel wavelength band. Note that the lower order linear phase dependence with wave number component is completely confounded with the inevitable imperfect fringe tracking. i.e. With our group delay fringe tracker, if there is a slight error in the position of the delay cart with respect to the true zero optical path, then this imparts a linear slope to the phase of the fringes as a function of wave number. In addition to adding phase curvature, the atmosphere also adds varying phase offsets. This phase offset is however a $N*2\pi$ wrapped quantity, where N can have values from zero to up to plus or minus several hundred, hence the atmospherically induced phase offset is not of much use. However, by determining the degree of phase curvature, we are able to correct for the random additional delay that the atmosphere adds. This gives us the "dispersion corrected" delays or in other words, the delays due only to geometry and any residual (over the measured) motion of the interferometer stations.

We first use the dispersion corrected delays and internal motion measurements to solve for the interferometer station positions. We allow for up to a third order polynomial time dependence (due to thermal effects throughout the night) for the station locations. We then use Markov chain Monte Carlo[4] with simulated annealing to determine the star position offsets from their ***apparent topocentric calculated positions***. In optical interferometery, the atmospherically induced phase changes of hundreds of 2π wraps, makes it impossible to do phase-offset measurements from distant (e.g. quasars) sources with well known positions, as is often done with radio interferometers[5,6]. This means that for full astrometric accuracy, we must use the full topocentric calculations, including the fully interpolated UT1 – UTC values throughout the night. We use the USNO NOVAS[7] routines for the stellar position calculations. We use code derived from interp.f[8], obtained from the International Earth Rotation & Reference Systems Service[9] (IERS) for interpolating UT1-UTC values between the daily tabulated values as provided by the IERS Rapid Service/Prediction Center.[10]

In the following series of plots and tables we show our current very preliminary distribution of UNAC offsets from the positions predicted from the Hipparcos catalog[11,12] (epoch 1991.25) updated to our UNAC epoch 2008. Within a few months we will be running our data through an improved data processing pipeline. Hence, we consider our current analysis very preliminary. At this preliminary stage, we are showing our results only in a statistical sense. We are not including the actual star designations.

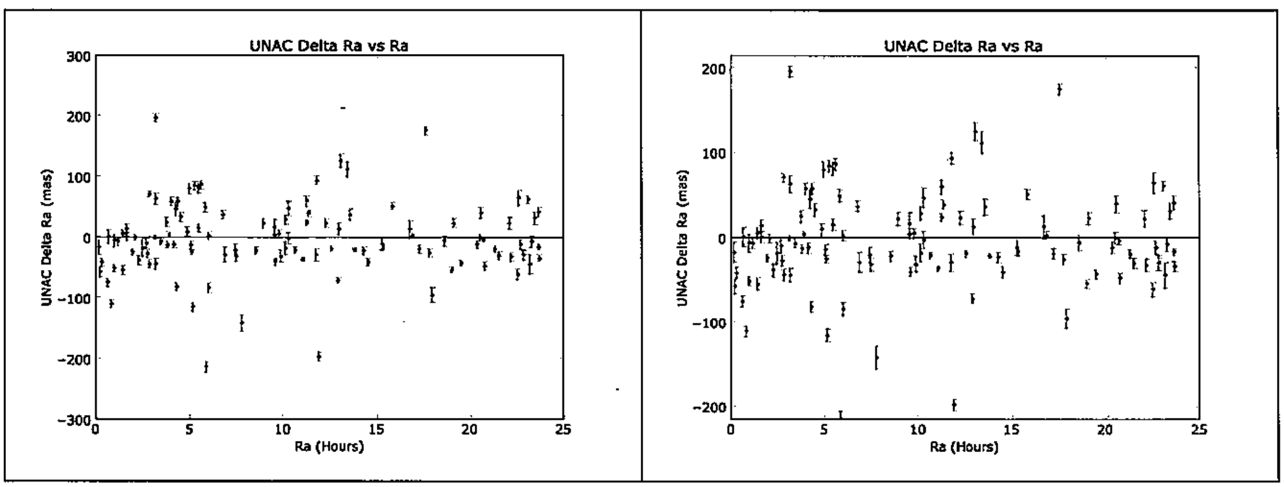

Figure 1. These panels show the distribution of the UNAC right ascension (Ra) offsets in mas from Hipparcos as a function of Ra. The right panel is a zoomed in view of the left panel.

Figure 1 shows the right ascension (Ra) differences in mas between our observed UNAC positions and the Hipparcos predicted positions plotted as a function of the star's Ra. There does not appear to be any obvious dependence of the position offsets with Ra. If such dependence were apparent, this would be an indication of systematic errors. There are, however some clear "by eye outliers" (BEOs). Table 1 describes the largest BEOs in the left panel of figure 1.

Table 1. Descriptions of the BEOs in Figure 1.

Delta Ra (mas)	Ra (Hours)	Comments
-111	0.8	Spectroscopic binary
195	3.2	Spectroscopic binary
-114	5.1	Low Dec
-214	5.9	Binary
-142	7.7	Binary
-198	11.9	Seems normal
174	17.7	Binary

Stars in binary systems are generally "difficult" astrometric candidates. They may have non-linear proper motion terms that need to be accounted for. Depending on the parameters of the binary system (including its distance), a full orbital solution may also be needed to predict the positions. At any rate, the binaries require special treatment in our analysis. At present, we have not provided them with the needed individualized analysis. Hence, it is not surprising that the outliers are primarily the few binary systems that we have in our data set.

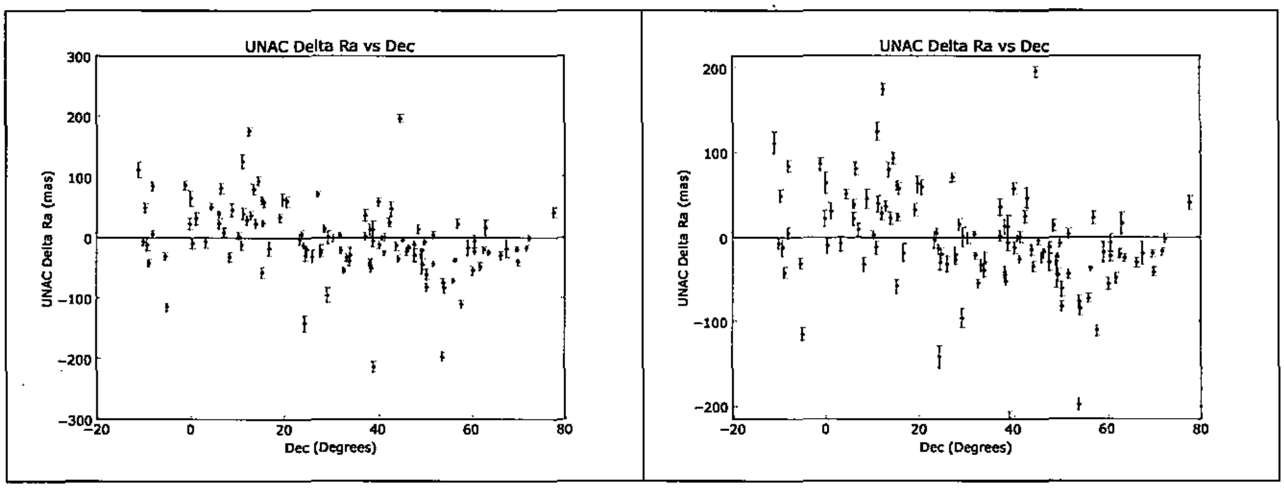

Figure 2. These panels show the distribution of the UNAC Ra offsets in mas from Hipparcos as a function of declination (Dec). The right panel is a zoomed in view of the left panel.

Figure 2 shows the Ra differences in mas between the observed UNAC positions and the Hipparcos predicted positions plotted as a function of the star's declination (Dec). Here, by eye, there is a slight indication of a negative sloping trend. After we do the final processing that we discuss in Section 4, we will do rigorous statistical tests to investigate any possible trends in these types of plots. Table 2 describes the largest BEOs in the left panel of figure 2.

Table 2. Descriptions of the BEOs in Figure 2.

Delta Ra (mas)	Dec (Degrees)	Comments
-116	-5.1	Low Dec
+174	12.6	Binary
-142	24.5	Binary
-214	39.1	Binary
+195	44.8	Binary
-198	53.7	Seems normal

As shown in Table 2, the BEOs are again dominated by the (same) binaries.

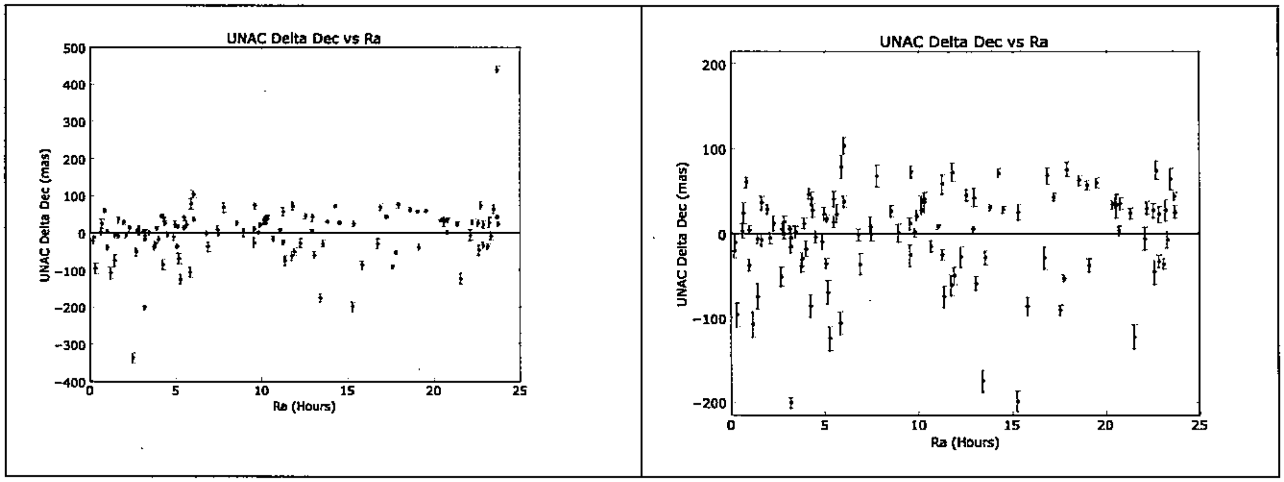

Figure 3. These panels show the distribution of the UNAC Dec offsets in mas from Hipparcos as a function of Ra. The right panel is a zoomed in view of the left panel.

Figure 3 shows the Dec differences in mas between the observed UNAC positions and the Hipparcos predicted positions plotted as a function of the star's Ra. Table 3 describes the largest BEOs in the left panel of figure 3.

Table 3. Descriptions of the BEOs in Figure 3.

Delta Dec (mas)	Ra (Hours)	Comments
-336	2.5	Binary
-200	3.2	Binary
-174	13.4	Low Dec
-199	15.2	Low Dec
+440	23.6	Binary

Binaries are again prevalent in Table 3.

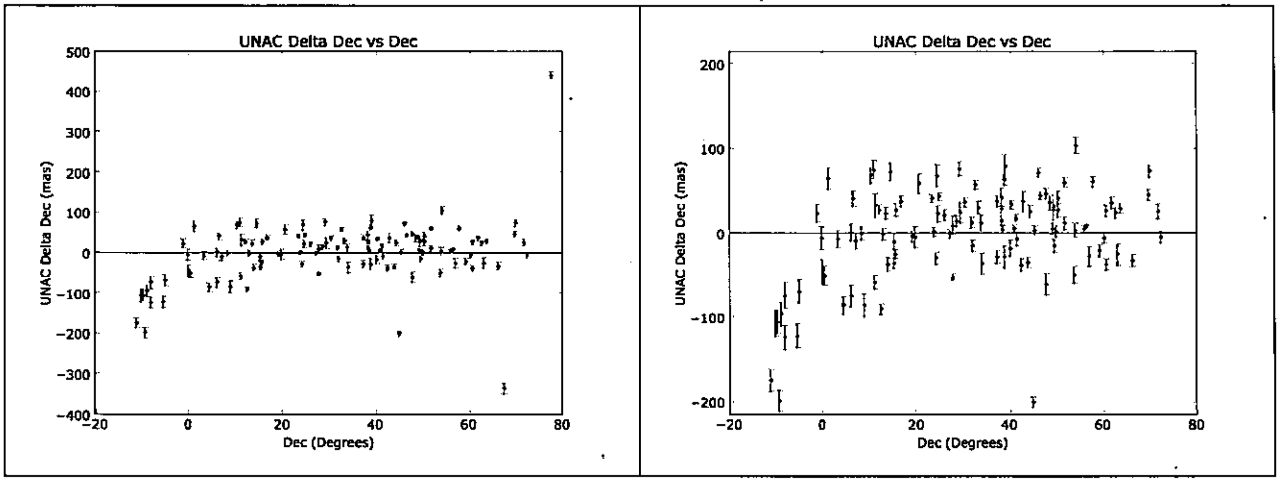

Figure 4. These panels show the distribution of the UNAC Dec offsets in mas from Hipparcos as a function of Dec. The right panel is a zoomed in view of the left panel.

Figure 4 shows the Dec differences in mas between the observed UNAC positions and the Hipparcos predicted positions plotted as a function of the star's Dec. This plot strongly indicates that we have a systematic problem for stars below a Dec of ~ 0 degrees. Above zero Dec, there is no obvious systematic pattern. Table 4 describes the largest BEOs in the left panel of Figure 4.

Table 4. Descriptions of the BEOs in the left panel of Figure 4.

Delta Dec (mas)	Dec (Degrees)	Comments
-200	44.8	Binary
-336	67.4	Binary
440	77.6	Binary

In this case all the BEOs are binaries. Note that all but one of the 7 binaries appear in more than one of the previous tables.

3. MEANS OF ASSESSING ACCURACY

3.1 Simple consistency check

The zeroth order sanity check on the accuracy of our offsets is to see how they compare on average with the Hipparcos position and proper motion uncertainties propagated to the current epoch. We show this very preliminary comparison in Figure 5.

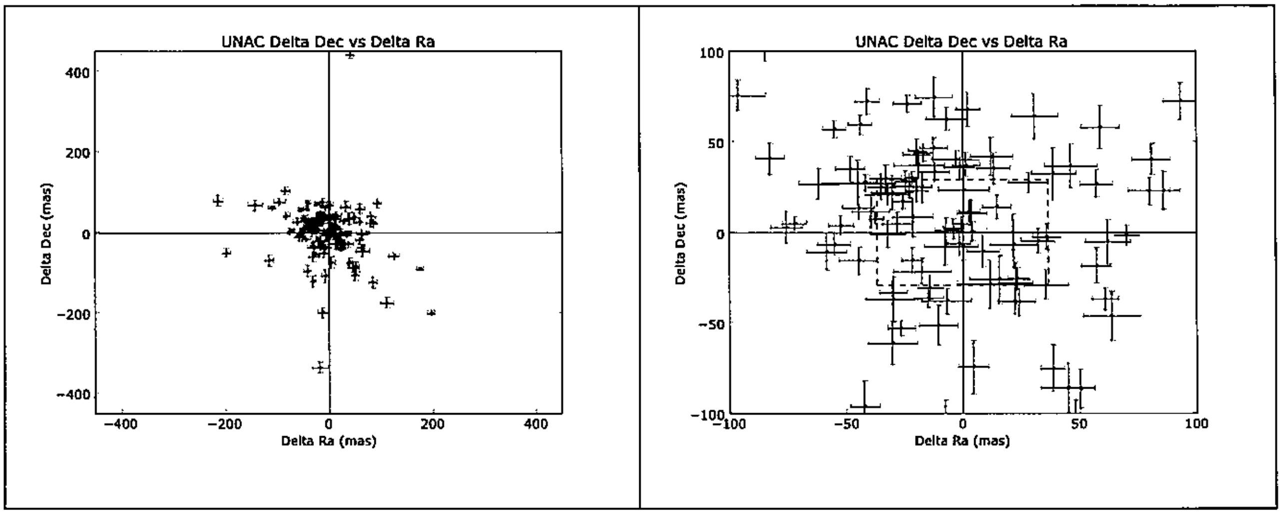

Figure 5. These panels show our positional offsets with respect to the calculated Hipparcos positions at the current epoch. The right panel is a zoomed in view of the left panel. The red dashed square on the right panel indicates the average (over our UNAC stars) 3-sigma limits for the Hipparcos positions and proper motions at the current epoch.

At this very preliminary stage, our offsets appear roughly consistent with Hipparcos errors propagated to the current epoch.

3.2 Checks with other high precision accurate catalogs

The FK6[13, 14] catalog combined data from the "Fifth Fundamental Catalog" (FK5)[15, 16] and the Hipparcos data in order to obtain improved proper motion precisions. The claimed improvements are factors of ~ 2-3 over the original Hipparcos results. A complete reanalysis of the Hipparcos data has also been performed by van Leeuwen (*Hipparcos, the new reduction*) [17]. With the two catalogs, we can therefore plot the difference in catalog predicted positions with respect to Hipparcos predicted positions for one catalog vs. the other and expect to see a high degree of correlation. Figure 6 shows this plot for our UNAC stars. While there is fairly good correlation, it is clear that there are some statistically significant differences between the catalogs.

3.3 Checks with Radio Interferometry astrometry

Radio interferometry is capable of very accurate and precise astrometry. It was radio interferometry observations that defined (and are still improving) the International Celestial Reference Frame[18, 19, 20] (ICRF). Unfortunately most optically bright stars are not bright in the radio. Hence, there have been very few recent (epochs ≥ 2000) radio interferometer astrometric measurements of optically bright stars. We do, however, have 4 UNAC stars that were within a set of 46 radio stars[5] that have radio astrometric positions determined in 2003. We are in the process of comparing our offsets with the radio interferometer measured offsets after updating to our epoch.

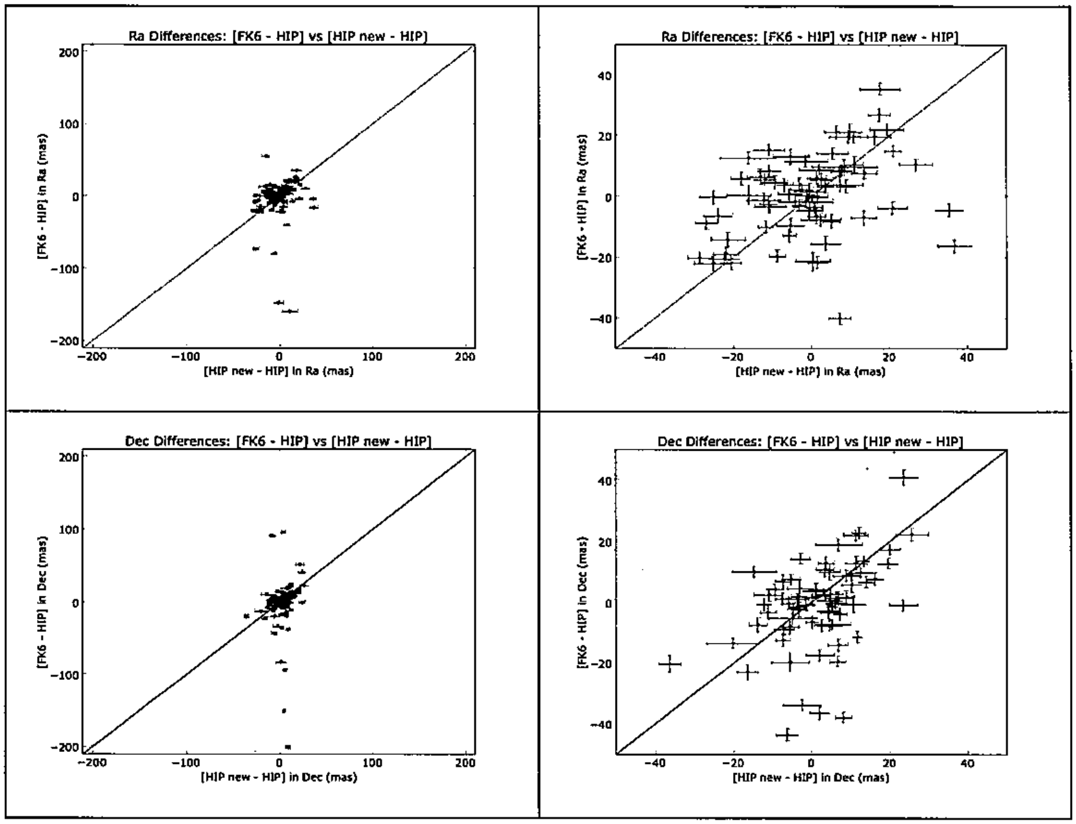

Figure 6. FK6 minus Hipparcos offsets are plotted vs. Hipparcos new reductions minus Hipparcos offsets in this figure. The top row shows the Ra offsets and the bottom row shows Dec. The right panels are zoomed in views of the left panels. The one-to-one correlation line is also shown.

4. CONCLUSIONS AND FUTURE PLANS

We have completed the optical interferometer observations that are needed to make a ~ 100 bright star astrometric catalog. At present we have 116 stars that show astrometric precisions < 16 mas. These high precision stars are a subset of stars for which we have precisions of < 50 mas.

The results that we show here are very preliminary. While we are encouraged that for positive declinations our current preliminary analysis does not show any obvious systematic effect, we certainly do not consider the checks we have done so far sufficient.

We will soon be running all of our data through an improved data processing pipeline. Our first run through our revision 1 data processing pipeline was meant from the beginning to primarily give us upper limit precision estimates on our offsets as we continued to collect enough data to meet our precision goal. Our revision 2 pipeline (P2) is meant to primarily give us accurate results and secondarily, we expect that it will also improve our precisions slightly. For the P2 processing run, we have:

1. Incorporated the recently released (31 Dec. 2009) NOVAS 3.0[7]. This updated NOVAS version has several improvements that, at the levels important for our UNAC catalog, significantly affect the accuracy of calculations of absolute (not differential) stellar apparent positions. Hence, due to this update alone, we expect that our offsets will significantly change when we do the P2 processing run.
2. For the P2 processing we will incorporate a more robust method that ensures that we only use data (in a per baseline manner) recorded during the time that the fringe tracker was truly locked on the fringe. This is necessary because during periods of bad seeing, we allow data to be recorded even if less than all baselines are simultaneously phased up. This data collection strategy is used because it allows us to collect possibly high signal-to-noise-ratio (SNR) baseline data even in the presence of other possibly much lower SNR baselines.
3. Finally, during our P2 processing we will do full simultaneous solutions that use all baselines present.

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